R.P. NOTE 124

TECHNICAL BASIS FOR EXTERNAL DOSIMETRY AT FERMILAB

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Introduction

The mission of Fermi National Accelerator Laboratory is to advance the understanding of the fundamental nature of matter and energy by conducting research at the frontier of high energy physics. As a result, Fermilab engages in the design, construction, commissioning, operation and, as necessary, decommissioning of particle accelerators and detectors. A system of particle accelerators provide beams for the conduct of experimental work in high energy elementary particle physics. Presently this consists of the Tevatron Collider experiments, several neutrino experiments, the 120 GeV fixed target program and several smaller test experiments. Fermilab also operates related support facilities which provide equipment components for the physics experiments and the operation of the physical plant of Fermilab. Radiological work is conducted in the radiation fields produced by the accelerators as well as with manufactured sources and materials radioactivated by the accelerated beams. Most radiological work at Fermilab involves maintenance and repairs on accelerator components that have been radioactivated by the particle beam. Sealed radioactive sources are utilized for calibration purposes and as important components of the particle detectors. Radioactive materials are sometimes incorporated as part of the experimental apparatus and beamline components. Work with all of these sources of radiation is a part of routine operations at Fermilab. The personnel who conduct such work must be monitored for exposure to ionizing radiation in accordance with federal regulation 10 CFR 835.

DOELAP

Fermilab maintains accreditation through the Department of Energy Laboratory Accreditation Program (DOELAP). DOELAP specifies a number of categories for the performance of dosimeters:

I. Low Energy Photon (High Dose)

II. High Energy Photon (High Dose)

IIIA. Low Energy Photon

IIIB. Low Energy Photon (Plutonium)

IV. High Energy Photon

VA. Beta

VB. Beta (Uranium)

VC. Beta (Special)

VI. Neutron

VII. Mixture Categories

Fermilab maintains accreditation in all DOELAP categories except IIIB and VC. These are unnecessary since Fermilab does not handle plutonium and has no significant sources of low energy beta exposure. These categories are described in detail elsewhere.[1,2]

Photon Radiation

DOELAP performance standards for low energy photons (Categories I and IIIA) include NBS filtered x-ray techniques which provide photons in the energy range of 20-120 keV. These energies are comparable to the low energy x-rays produced by elements of the Fermilab accelerators, e.g., the linac and other RF systems. These elements may emit x-rays in the energy range from 20 to 180 keV. Some instrument check sources such as ^{55}Fe are also in use at Fermilab, but the 6 keV x-ray from ^{55}Fe decay is below the energy range addressed by DOELAP and is not considered an external radiation hazard (see Appendix A).

DOELAP performance criteria for high energy photons (Categories II and IV) uses a sealed ^{137}Cs source which emits 662 keV gamma rays. Photon radiation at Fermilab which presents the major occupational exposure concern comes primarily from activated items which include, beamline components, shielding materials, experimental apparatus, etc. The radionuclides typically found in such items are mainly ^{22}Na, ^{54}Mn and ^{60}Co. A variety of radionuclides are also produced in smaller quantities. These isotopes primarily emit gamma radiation with energies between 0.5 and 1.5 MeV, which is comparable to the ^{137}Cs photon energy.

Beta Radiation

The standard for DOELAP category VB is a slab of natural or depleted uranium, with maximum beta energy of 2.3 MeV. Fermilab does have an inventory of depleted uranium, most of which is enclosed within the D0 detector, and related devices, and is inaccessible under normal operating circumstances. Beam targets made of depleted uranium have also been used, but these are located in exclusion areas and are also inaccessible under normal operating circumstances. Due to the eventual disassembly or modification of the D0 detector, Fermilab continues to maintain accreditation in Category VB.

The standard for DOELAP category VA is a point source of ^{90}Sr/^{90}Y with a maximum beta energy of 2.3 MeV. Beta radiation is produced by beta/gamma emitting activation products at Fermilab as previously described. However, beta radiation is less of a concern than gamma because, with few exceptions, radioactive materials at Fermilab are produced by volume activation of materials. Since the radionuclides are distributed throughout the depth of the activated item, rather than being concentrated on the surface, most of the beta radiation is absorbed within the material. Exceptions to this rule include small sealed sources containing beta emitters, occasional surface contamination involving beta emitters, and the use of depleted uranium in experimental apparatus and beamline components.

The most common beta sources in use at Fermilab are ^{90}Sr and ^{106}Ru. The maximum beta energy from the decay of ^{60}Co , the most common, and exceptionally long lived activation product of potential concern in this context, is about 0.32 MeV.

Neutrons

Neutrons are produced at Fermilab under beam-on conditions by the interaction of the beam with beamline components, targets, or beam dumps. At the point of their production, the neutrons may have extremely high energies, almost up to the level of the primary beam energy. Such high energy neutrons are produced only in exclusion areas where no personnel would be present during beam-on conditions. Some of the neutrons, however, may filter out through labyrinths, penetrations, or shielding, producing neutron fields in areas where personnel may be exposed. Another potential source of neutron exposure at Fermilab is the use of encapsulated neutron sources, such as ^{241}AmBe or ^{252}Cf.

The DOELAP standard for neutron dosimetry (Category VI) is a ^{252}Cf source. While both unmoderated neutrons and neutrons moderated by 15 cm of D_2O, are available as DOELAP categories, Fermilab is accredited in the unmoderated neutron category. The neutron spectrum from unmoderated ^{252}Cf is smooth with an average energy of 2.4 MeV[3], and most closely represents the neutron energy spectrum at Fermilab. The moderated source has a broad peak spanning several decades of energy roughly centered on 0.02 MeV as well as a reduced peak in the 2.4 MeV region.

Dosimeters

The dosimeter of record currently in use at Fermilab, to monitor the types of radiation potentially encountered at the lab, is Landauer's InLight LDR Model 2 dosimeter. The detector element for beta/gamma is a layer of Al_2O_3 sandwiched between two layers of polyester. It is used with a set of metal and plastic filters to differentiate photon energies. These filter materials, plastic, copper and aluminum, are capable of distinguishing between various photon energies and the different levels of penetrating dose: 7 mg cm^{-2} (shallow), 300 mg cm^{-2} (lens of eye), 1000 mg cm^{-2} (deep dose).

Optically Stimulated Luminescence (OSL)[7] is the method of analysis applied to the detector. This is similar to Thermoluminescent Dosimeters (TLD)[4], however, instead of using heat to release radiation excited electrons back to lower energy states, OSL uses light.

OSL material, using aluminum oxide crystals, provides many advantages over TLD dosimetry including very little fading over time, impervious to environmental factors (temperature, pressure, etc.) and re-read capabilities. Fermilab used TLD for many years and before making the transition to OSL, this technology was thoroughly evaluated for use at Fermilab, which included intercomparison studies and double badging of selected individuals. These studies are available for review in the Dosimetry Program Office.

Although high energy neutrons are present at Fermilab, no standard for high energy neutron dosimetry presently exists. Of the current technologies available, track-etch dosimetry is one of the most effective at detecting high energy neutrons[1], such as those potentially present at Fermilab. Industry studies have indicated that polycarbonate (trade name CR-39) materials are the most sensitive to the higher energy neutrons. Fermilab therefore uses CR-39, with a polyethylene radiator, in the InLight dosimeter to monitor neutrons.

The adequacy of track-etch detectors for neutron dosimetry at Fermilab has been established by studies of neutron fields at Fermilab[4, 5] and by the demonstrated sensitivity of CR-39 to higher energy neutron fields both in published literature[4] and as verified by blind audit results ("badge spiking").

Thermal neutrons are not generally a consideration for personnel exposures at Fermilab, therefore the InLight dosimeters do not contain a Boron radiator behind the CR-39.

Supplemental Dosimetry

In addition to a primary dosimeter, supplemental dosimetry is sometimes used to obtain an immediate reading of the integrated dose. Obtaining an instant dose measurement instead of waiting for a badge to be processed serves three basic purposes:

• The wearer can determine if a large or significant dose has been received during the badge wear period so that work may be planned for the remainder of the wear period to keep doses ALARA.

• An unexpected dose might indicate the presence of an unanticipated radiation hazard or the need for a revised work procedure.

• If a primary dosimeter should be lost, the pocket ion chamber provides some data to help complete an exposure investigation.

The pocket ion chamber is an industry standard and is well-suited to this role. As indicated above, they are sensitive to both gamma and muon radiation, which are the major dosimetry concerns at Fermilab. Although these dosimeters are relatively insensitive to neutrons, Fermilab does not typically have "neutron only" radiation fields, but rather mixed radiation fields. Where there are neutrons, there will also be gammas and/or muons, so that the pocket ion chamber will be able to serve adequately in a supplemental role. The pocket ion chamber is also insensitive to beta radiation but, as described above, beta exposures are relatively rare at Fermilab.

Accident Dosimetry

Fermilab does not use accident dosimetry in the ordinary sense of the word. This term is usually applied to nuclear criticality accidents, the conditions for which do not exist at Fermilab. The characteristic accident at Fermilab which would result in a large dose is a direct beam-on exposure. In such an incident, most of the dose would come from high-energy hadrons. Track-etch foils are sensitive to such radiation but are saturated at doses of a few rads. However, a high energy particle beam will activate matter which is exposed to it, including the human body. The amount of induced radioactivity is dependent on the dose received. If an individual were to suffer a beam-on exposure, the procedure for dose reconstruction is through the use of a whole body counting apparatus. A dose is estimated based on the radioactivity induced in the person's body.[5] The body counting apparatus at Fermilab is suitable only for making a preliminary estimate of the dose. This equipment and procedures are located at the Beam On Dose Assessment

(BODA) Facility at Site 39, south annex. A more detailed assessment could be made later using the whole body counting facilities at Argonne National Laboratory.

Conclusion

Fermilab's mission as a research facility for high energy physics results in a variety of radiation fields to which personnel may be exposed. These include both prompt radiation and residual radioactivity from activated items. The prompt radiation hazards under normal occupational conditions consist primarily of neutrons and muons (not addressed by DOELAP). The radiation hazard from residual radioactivity is primarily gamma rays. Beta radiation is a comparatively minor concern.

The radiation hazards cited above justify the need for DOELAP accreditation in the categories I, II, IIIA, IV, VB, VC, VI. Since more than one type of radiation may be present in some areas, the need for some Category VII mixtures, such as gamma + neutron, is also justified.

For a primary dosimeter, Fermilab currently uses a combination of OSL material and a polycarbonate (CR-39) track etch detector. This combination, supplemented by pocket ion chambers, as necessary, is well suited to the occupational radiological environment at Fermilab. Insofar as there is no standard for some types of radiation which are found at high energy accelerators such as high energy neutrons and muons, dosimetry for them needs to be based upon information available from existing studies. Fermilab has made considerable contributions to this field of research and will endeavor to make further contributions so as to provide the best possible dosimetry for all relevant radiation fields.

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Appendix A

^{55}Fe Sources At Fermilab

Fermilab typically maintains in its inventory of sealed radioactive sources a number of ^{55}Fe sources ranging in activity from a few microcuries to several millicuries. The 6 keV x-ray emitted by this nuclide is outside the sensitivity of many commercially available personnel dosimeters. The question considered here is whether it is necessary that Fermilab's personnel dosimetry be sensitive to the radiation of ^{55}Fe. The x-ray is of such low energy that it poses no deep dose hazard, therefore the shallow dose only is considered here. From Shleien[6], the flux to dose equivalent rate for photons in the energy range from 10 - 30 keV is given by

$$\ln D(E) = -20.477 - 1.7454 \ln E \qquad (\text{rem/hr})(\text{cm}^2\ \text{s}) \qquad (\text{A.1}),$$

where E is the photon energy (MeV). The constants, taken from Table 6.1.1 of the reference, represent the lowest energy range for which the numbers are available, but still somewhat higher than the 6 keV of ^{55}Fe. Solving for D,

$$D(6\ \text{keV}) = 3.73\ (\mu\text{rem}/\text{hr})(\text{cm}^2\ \text{s}) \qquad (\text{A.2}).$$

Assume that 1 rem shallow dose equivalent, 2% of the allowed regulatory annual limit, is the lowest dose of concern and an hour is a typical time spent working in close proximity to the source. Equation (A.2) can then be used to determine what flux F of ^{55}Fe photons would produce a shallow dose equivalent of one rem.

$$F = \left(3.73 \times 10^{-6}\right)^{-1} = 2.68 \times 10^{5}\ (\text{s}^{-1}\ \text{cm}^{-2}) \qquad (\text{A.3}).$$

Assume next that the source (approximately a point source) is 30 cm away from the trunk of the body of a Standard Man, which has an area S of 3240 cm^2. The rate at which photons which must impinge on the trunk of the body to deliver a dose equivalent of one rem in one hour is

$$N = FS = 8.68 \times 10^{8}\ \text{s}^{-1} \qquad (\text{A.4})$$

One must consider here the attenuation of 6 keV photons in air. Referring again to Shleien for the attenuation coefficient, a simple calculation shows that a beam of 6 keV photons is reduced to 43.6% of its original intensity after passing through 30 cm of air. Clothing further attenuates the 6 keV photons. Again using numbers from Shleien and assuming a 0.05 cm layer of nylon approximates the effect of a shirt, the radiation is reduced to 54.8% of what penetrates the 30 cm of air. This attenuation introduces a correction factor *c*.

The activity of a source delivering a one rem dose equivalent is

$$\begin{aligned} A &= N\frac{Sc}{4\pi r^2} = \frac{8.68\times10^8}{(0.436)(0.524)}\frac{3240\ \text{cm}^2}{4\pi(30\ \text{cm})^2} = 1.09\times10^8\ \text{Bq} \\ &= 29.4\ \text{mCi} \end{aligned} \qquad (A.5).$$

This activity is a more than an order of magnitude higher than any ^{55}Fe source in Fermilab's inventory. The calculation is based on a very conservative estimate of the solid angle since at this distance, the body would not approximate a spherical surface very well and the geometry would actually make the body a smaller target than is indicated here. Even with these assumptions, however, it is seen that the ^{55}Fe sources in Fermilab's inventory will not deliver significant doses. There is, therefore, no need for dosimeters sensitive to such radiation.

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[1] U. S. Department of Energy, *Handbook for the Department of Energy Laboratory Accreditation Program for Personnel Dosimetry Systems*, DOE/EH-0026, December 1986.

[2] U. S. Department of Energy, *Department of Energy Standard for the Performance Testing of Personnel Dosimetry Systems*, DOE/EH-0027, December, 1986.

[3] International Organization for Standardization (ISO), 1986, *Neutron Reference Radiations For Calibrating Neutron Measuring Devices Used For Radiation Protection Purposes And For Determining Their Response As A Function Of Neutron Energy*.

[4] N. E. Ipe, J. C. Liu, B. R. Buddemeier, C. J. Miles, and R. C. Yoder, 1991, *A Comparison of the Neutron Response of CR-39 Made by Different Manufacturers*, Proceedings of the 7th Symposium on Neutron Dosimetry, Berlin, Germany.

[5] A. Elwyn and C. Salsbury, 1990, *Dose Estimates at the Body Counter Facility*, Fermilab Radiation Physics Note 85.

[6] B. Shleien (editor), 1992, *The Health Physics and Radiological Health Handbook*

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[7] M. Akselrod, A.C. Lucas, J.C. Polf, S.W.S. McKeever, 1998, *Optically Stimulated Luminescence of Al_2O3,* Radiation Measurements 29:391- 399.